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Correlation of Optical Emission and Ion Flux with GaN Etch Rate in Inductively Coupled Ar/Cl₂ Plasma Etching

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The etching of GaN was investigated in an Ar/Cl₂ inductively coupled plasma. Optical emission spectroscopy and an ion flux probe were used to obtain insight into the etch mechanisms during processing. Langmuir probe measurements were also used to determine the basic Ar/Cl₂ plasma characteristics. Etch rates of ≈ 500 nm/min were obtained at relatively low Cl₂ fractions of $\approx 50\%$. The dominant emission species observed were Ga (at 294 nm) and up to six GaCl peaks between 320 and 345 nm. Plasma characterisation and ion flux indicate etch mechanisms that depend strongly on atomic chlorine but with increasing power and at low Cl₂, the significance of ion-based processes cannot be ruled out.

Introduction Advances in device fabrication based on group III nitrides will depend on device processing development including dry etching. Etch requirements are complicated by the fact that III–V nitrides etch at much slower rates than conventional III–V compounds. In general chlorine based gases are used for etching due to high volatility of group III chlorides [1] and etching is typically accomplished in reactive ion systems where the self-bias provides the accelerating field for positive ion bombardment. High density etch systems have, however, recently attracted attention. Inductively coupled plasmas (ICPs) have plasma densities between two and four orders of magnitude higher than capacitive reactive ion systems [2]. In addition the substrate bias is applied externally allowing for separate optimisation of plasma and substrate power inputs. Etching has been carried out using a range of plasma systems but little detailed investigation of GaN etching mechanisms has been undertaken and the plasmas used have not been well characterised [3]. We have used optical emission spectroscopy to gain a qualitative estimate of relative species densities during etching. Correlation between etch rate variation and the volatile emission ratios can provide indications of chemical and physical activities and their relative significance. Investigation of internal plasma characteristics has been undertaken but due to the extremely corrosive environment, the application of these techniques has been restricted to the low power regime. We also report results from an ion flux probe, a non-invasive continuous sensor, insensitive to surface deposition, mounted on the grounded chamber wall [4]. A capacitor is charged by a pulsed RF voltage and discharged by the positive ion flux.

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Experimental Inductive power is input to the planar coil at 13.56 MHz and the substrate DC bias voltages, -140 V to -200 V, were generated by a 14 MHz RF power supply. GaN layers on sapphire (≈ 4.5 cm²) were used for all experiments. Chlorine fraction was varied from 0% to 100%, flow rates 5 to 20 sccm, at a pressure of 10 mTorr. Optical emission peaks (Monolight Instruments Ltd) were measured through a MgF₂ window at a distance ≈ 225 mm. Reference background spectra were taken for each process condition. A window of 275 to 360 nm was selected to obtain spectra during the etching of GaN. A guard ring ion flux probe (Scientific Systems, Dublin), mounted on the chamber wall and driven by a 20 W, 10 MHz RF pulse was used to measure positive ion flux during processing. Compensated Langmuir probe IV measurements were obtained without a sample in place. Electron densities were estimated from the calculated electron energy distribution function while ion densities were estimated from the IV ion-saturation region.

Results and Discussion Figure 1 shows the comparison between the reference spectrum (no sample) and spectra taken during GaN etching at 50% Cl₂, 400 W drive power, 10 sccm and -200 V bias voltage. The reference spectrum shows two broad bands, one at 300 to 315 nm attributed to the Cl₂ molecule and the other with a maximum at ≈ 380 nm, attributed to Cl₂⁺ ions [5]. From the etch spectra, the significant etch species peaks for Ga, GaCl, and N₂ are visible above these bands. At 0% Cl₂, peaks for Ga and N₂ were observed, as in Fig. 1, and with the introduction of chlorine, the GaCl signal peaks become apparent between 320 and 345 nm. We have observed up to four peaks in the range 320 to 345 nm during etching, which can be attributed to GaCl ($A^3\Pi_0 - X^1\Sigma^+$ and $B^3\Pi_1 - X^1\Sigma^+$) [5]. In Fig. 2, the etch rate increases with Cl₂ fraction, saturating at ≈ 500 nm/min beyond 50%. This is commensurate with literature reports on etch rate which vary between 350 to 1300 nm/min, depending on plasma excitation (MRIE, ECR, and ICP) and gas chemistry (BCl₃, ICl/Ar and Ar/Cl₂) [6–8]. In these cases, typical halogen gas fractions have been high ($>90\%$). With 100% Ar, a high sputter rate has been observed, which has not previously been reported. Also shown in Fig. 2 is the excited Ga emission intensity (294 nm), which varies inversely with etch rate, and positive ion flux, which also falls with increasing Cl₂ fraction. In

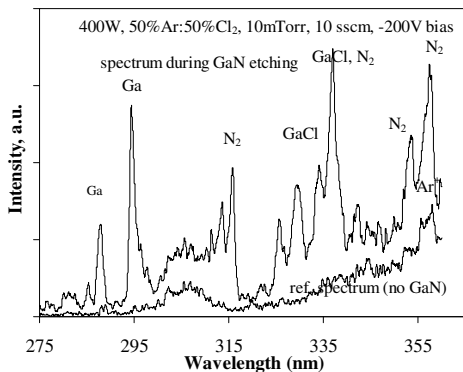


Fig. 1

Fig. 1. Optical emission spectra with and without GaN wafer

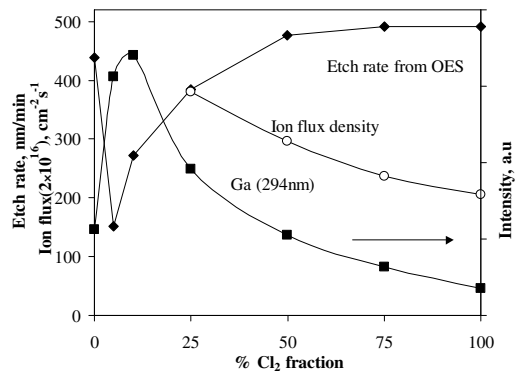


Fig. 2

Fig. 2. Etch rate, peak Ga emission intensity (294.5 nm), and ion flux variation with %Cl₂

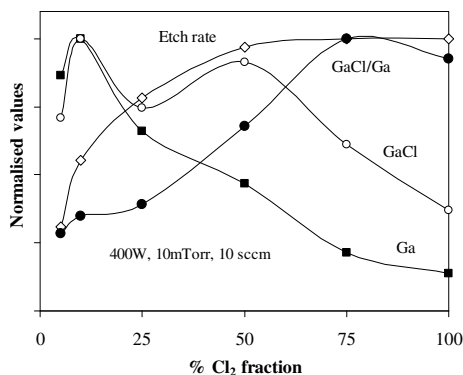


Fig. 3

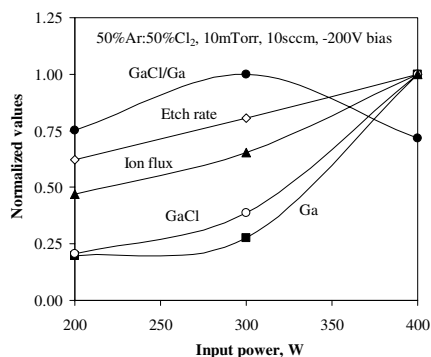


Fig. 4

Fig. 3. Variation in normalised etch rate, flux, and Ga, GaCl, and GaCl/Ga emission with %Cl₂

Fig. 4. Etch rate, flux, and Ga, GaCl, and GaCl/Ga emission intensity variation with power

Fig. 3, the variation in GaCl peak emission obtained from the sum of all peaks (320 to 345 nm) is shown in comparison with Ga peak emission and the ratio GaCl/Ga. The etch rate variation with power was found to be linear, Fig. 4. Peak emission from the Ga (294 nm) and from GaCl lines was also found to increase, as did positive ion flux. The ratio GaCl/Ga reached a maximum before falling.

The use of emission intensities as indicators of etch species concentrations and mechanisms must be treated with caution as emission cross-sections vary widely between species and across the plasma energy spectrum. Measurements of Cl, Cl⁻, electron, and ion densities, in Ar/Cl₂ present considerable difficulties especially at high powers and with sample in place. Nevertheless we can obtain some useful indications from our low power (no sample) investigations, currently in progress [9]. Cl density, determined by laser-induced fluorescence, increased with % Cl₂, rapidly between 0% and 10%, more slowly thereafter. It was also observed to increase with both power and pressure. The negative ion fraction saturates at <10% for most process conditions. The increase in etch rate with % Cl₂, followed by saturation, Fig. 2, matches the trend in atomic Cl density, at low power, indicating a strong chemical element in the etch mechanism. While both Ga and GaCl intensities fall with etch rate, the more rapid

decrease in the former suggests GaCl as the chemically derived volatile and Ga as more dependent on physical ion-based processes. In Fig. 5, positive ion densities within the plasma measured by Langmuir probe, at 400 W

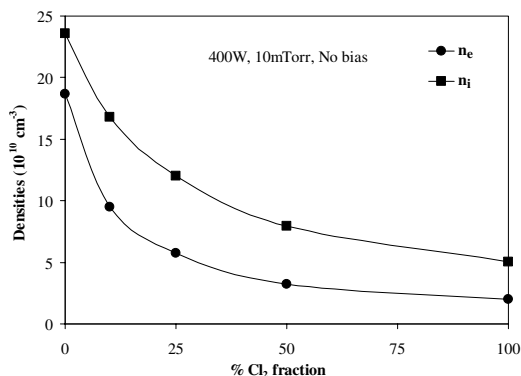


Fig. 5. Positive ion and electron densities measured by Langmuir probe

power, show a rapid fall as Cl_2 fraction is increased. This decrease in the number of positive ions within the plasma and a similar decrease in ions reaching the wall, as measured by the flux probe, are further evidence for this hypothesis. Chemical and physical mechanisms cannot be simply isolated however, as the case for pure sputtering at 100% Ar shows. At low powers, (0 to 100 W) we note an increase in atomic Cl density with power, with little tendency to saturation. We may infer that the increased etch rate, Fig. 4, is due to a higher Cl concentration giving a dominance of GaCl species. Nevertheless, the ion flux and the Ga intensity were also observed to increase while the GaCl/Ga fell at >300 W. Ion flux is a good indicator of physical ion-based reactions at the GaN surface. Ion probe measurements in the range 0 to 400 W show an estimated increase in positive ion density by two orders of magnitude, at 50% Cl_2 .

Conclusion ICP high rate etching of GaN has been shown with relatively low halogen concentrations (50%) while plasma diagnostics have indicated the importance of atomic Cl chemical reactions for etching. Nevertheless under such process conditions, the effects of ion-enhanced may well be significant, as indicated by ion density and ion flux measurements. The nature of etch mechanism is important since both high etch rates and etch anisotropy are required, the later dependant upon directional ion-bombardment. The use of simple twin diagnostic probing can now be used to explore the full parameter space, including applied bias and pressure effects, in order to optimise process conditions.

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